Overview of laser systems for the Orion facility at the AWE

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The commissioning of the Orion laser facility at the Atomic Weapons Establishment (AWE) in the UK has recently been completed. The facility is a twelve beam Nd:glass-based system for studying high energy density physics. It consists of ten frequency-tripled beam-lines operating with nanosecond pulses, synchronized with two beam-lines with subpicosecond pulses, each capable of delivering 500 J to target. One of the short pulse beams has the option of frequency doubling, at reduced aperture, to yield up to 100 J at 527 nm in a subpicosecond pulse with high temporal contrast. An extensive array of target diagnostics is provided. This article describes the laser design and commissioning and presents key performance data of the facility’s laser systems.

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1. Introduction

The Atomic Weapons Establishment (AWE) has an enduring need to maintain expertise in high energy density physics to sustain confidence in the UK’s nuclear deterrent in the absence of underground testing. The construction of the Orion laser facility was recognized as a necessary development, extending AWE’s capability beyond that of the HELEN laser [1], Orion’s predecessor. The facility generates matter under extreme conditions of temperature and pressure, and is therefore of interest to communities including astrophysics, materials properties, and inertial confinement fusion. It will also be used in support of the wider academic community with the provision of 15% of beam-time to external users.

Orion utilizes a combination of ten “long pulse” (nanosecond) beam-lines and two “short pulse” (sub-picosecond) beam-lines to create and diagnose matter that is simultaneously hot and dense. For example, in a typical experimental scheme, long pulse beams shock (or otherwise compress) a sample of interest. One short pulse beam then heats the material rapidly and the other provides x-ray backlighting with high temporal resolution.

A schematic of the facility is shown in Fig. 1. The laser hall is 80 m in length and contains two large space frames. The larger of these supports the ten long pulse beam-lines in two stacks of five. The ten long pulse beam-lines deliver temporally shaped pulses with duration of between 0.1 and 5 ns. The baseline design pulse, which is square with 1 ns duration, delivers 500 J at the third harmonic (351 nm) in each beam-line. Upon transport into the target hall, a set of five dichroic mirrors remove the residual fundamental and second harmonic light and also transform the architecture from a rectilinear geometry to a conical one.

The smaller laser hall space frame supports two short pulse beam-lines, which are chirped pulse amplification (CPA) systems, each specified to deliver 500 J around 1054 nm in a 500 fs pulse. The short pulse beams, after amplification, are expanded to
600 mm diameter and directed into the compressor hall. This room houses two single-pass compressors, each using two gold-coated, 940 mm-diameter diffraction gratings, similar to those used on the Vulcan system at the Rutherford Appleton Laboratory [2], mounted within large evacuated vessels. Beam transport from this point is all in vacuum through to the target chamber. The short pulse beams are focused using \( f/3 \) off-axis parabolic mirrors, in orthogonal directions. On one short pulse beam-line, an additional chamber after the compressor houses a 300 mm diameter potassium dihydrogen phosphate (KDP) crystal for frequency doubling the compressed pulse at subaperture. In this (optional) configuration, up to 100 J of \( \sim 527 \) nm light in roughly 500 fs is realized with greatly enhanced pulse contrast.

The target hall itself is approximately 20 m on each side, with a 1.5 m thick concrete wall to act as a biological shield from the x rays produced during the short pulse interaction with the target. There are two rigid steel structures on either side of the room to house beam turning mirrors and laser diagnostics.

The targets are mounted from a 4-axis stage (x, y, z, azimuth) with micron accuracy. An extensive suite of target diagnostics is provided, including x-ray, optical, neutron, and charged particle detectors. Some diagnostics are mounted directly from the target chamber and others are fielded in one of six ten-inch manipulators (TIMs). A diagnostic is inserted in a TIM within an airlock and then deployed close to target without the need to break vacuum in the target chamber. The TIMs also facilitate fine pointing adjustments of their diagnostics.

The pulsed power system is situated beneath the laser hall, on the ground floor. This is comprised of 14 capacitor bank modules with a total stored energy of 8 MJ. These supply the disk amplifiers and Faraday rotators within the facility. Also on the ground floor are the optical pulse generation systems for the long pulse (OPG1) and short pulse (OPG2) systems.

2. Long Pulse Laser Description

A. Pulse Generation and Preamplification

The long pulse generation and preamplification system has been published previously, after the prototyping stage [3]. The architecture is shown schematically in Fig. 2. The light source is a 1 W, 1053 nm commercial distributed feedback fiber laser, from which is chopped a 1 kHz train of \( \sim 400 \) ns pulses using a fiber-coupled acousto-optic modulator. Fine pulse-shaping occurs later in an integrated-optical (IO) modulator. The reason for converting the CW beam into a low duty-cycle train of 400 ns pulses is that the average power in the modulators is reduced greatly. This negates the drift of the zero-transmission bias voltage on the integrated optical modulators that is seen when higher average optical power is injected into these devices. The IO modulators take electrical inputs from an arbitrary waveform generator (AWG) and a fast rise/fall time square pulse generator to yield user-defined pulse shapes with a rise time of less than 100 ps. The output from each IO modulator has a peak power of \( \sim 50 \) mW, which is sufficient to dominate the amplified spontaneous emission in the later amplifiers (principally a regenerative amplifier) by a factor of \( 10^3 \), without the need for dedicated fiber amplifiers. The contrast ratio of the of the IO modulator optical output is has been measured as \( 2 \times 10^4 \).

Each IO modulator output is fed via fiber to a preamplifier module (PAM), situated in the laser hall. The PAMs are double-sided breadboards, mounted along one edge, 5.5 m in length and 1.5 m in height. They incorporate a flashlamp-pumped Nd:YLF regenerative amplifier, a spatial beam shaping stage, 2D smoothing by spectral dispersion (2D-SSD), and a flashlamp-pumped, 32 mm aperture, four-passed rod amplifier stage. The 2D-SSD system uses a pair of phase modulators [4,5], operating at 2.45 and 10.4 GHz, the bandwidth from each being dispersed.
in orthogonal planes by diffraction gratings at the Littrow angle. Additional gratings precompensate the lateral temporal shear across the beam seen upon diffraction. Operation with either dimension of SSD is optional, merely by energizing the appropriate phase modulator. An SSD capability in two dimensions, with modulation at dissimilar frequencies, was included in the facility specification to provide enhanced focal spot smoothing and facilitate directly driven experiments. The rod amplifier head uses Nd:phosphate glass and is of the same design used on the National Ignition Facility [6]. Four passes of the rod are engineered using angular separation in the near-field (see Fig. 3). An array of four pinholes at the focal plane of the TSF spatially filters the beam while blocking the principal axis of the beam-line, so as to inhibit oscillation. The beam is injected near the focal plane of the TSF and directed through the first pinhole. It is collimated at 170 mm diameter before undertaking a double pass of the amplifiers. The end-mirror is aligned orthogonal to the beam-line axis, so that the reflected beam passes through the pinhole diagonally opposite pinhole 1. The beam is then picked off at 16 mm diameter by a small mirror inside the TSF and diverted to a “reverser” system. This collimates the beam at 40 mm diameter, double-passes a gain isolating Pockels cell and returns the beam to the pinhole plate, through the pinhole directly below pinhole 2. A further double-pass of the amplifiers ensues and the beam passes through the final pinhole, which is above pinhole 1. The beam misses the inject and reverser pick-off mirrors and continues to the other end of the TSF, where it is collimated at 300 mm diameter. The beam-line end-mirror and the reverser end-mirror are at mutual image planes. This makes alignment of the system straightforward.

The laser amplifiers contain three disks of 4% wt. Nd-doped Schott LG770 glass, mounted at Brewster’s angle (this glass is used in all disk amplifiers in the facility). A cassette holding four 1120 mm arc-length, 25 mm bore flashlamps is mounted on each side of the amplifier. The atmosphere within the amplifier body is maintained with a purge of “clean dry air” (CDA), which is actually a mixture of pure N\textsubscript{2} and O\textsubscript{2} gas. Immediately after a shot, high efficiency particulate air (HEPA) filtered ambient air is forced through the lamp cassettes to achieve prompt cooling and prevent residual heat from conducting into the disks. Also, the flow rate of the CDA is increased adjacent to the disks.

**B. Long Pulse Amplifier Chain Design**

The long pulse laser chain is defined by a 34 m long transport spatial filter (TSF). Four passes of four 200 mm aperture disk amplifiers are engineered using angular separation in the near-field (see Fig. 3). A 2D-SSD system is used to spatially filter the beam and block the principal axis of the beam-line. Each pass is followed by a spatial shaper to form a top-hat beam. The beam is then injected into the first pinhole and directed through the TSF. It is collimated at 170 mm diameter before undergoing a double pass in the amplifiers. The end-mirror is aligned orthogonal to the beam-line axis, so that the reflected beam passes through the pinhole diagonally opposite pinhole 1. The beam is then picked off at 16 mm diameter by a small mirror inside the TSF and diverted to a “reverser” system. This collimates the beam at 40 mm diameter, double-passes a gain isolating Pockels cell and returns the beam to the pinhole plate, through the pinhole directly below pinhole 2. A further double-pass of the amplifiers ensues and the beam passes through the final pinhole, which is above pinhole 1. The beam misses the inject and reverser pick-off mirrors and continues to the other end of the TSF, where it is collimated at 300 mm diameter. The beam-line end-mirror and the reverser end-mirror are at mutual image planes. This makes alignment of the system straightforward.

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With the capacitor banks charged to 22 kV, a total of 145 kJ is discharged through the lamps in a 490 μs (FWHM) pulse. The resultant small signal gain is 2.45 per amplifier. This would result in a double-pass gain in the beam-line of around 1300, with the associated danger of oscillation. In practice, the capacitor banks are charged to around 18 kV, with a gain of 2.08 (double-pass net gain ~350). This corresponds to a total stored energy within the aperture of all the amplifiers of 4.45 kJ.

The threat of oscillation between the end-mirror and another reflecting surface is mitigated by tilting the TSF lenses such that no reflection from any point on their surfaces can create a closed path through the amplifiers. Also, reflective metallic surfaces within the TSF structure must be suitably baffled. The only lines of sight from one side of the focal plane to the other are through the pinholes. The lenses of the TSFs are reversed (i.e., their curved surfaces face the pinholes) to limit the power of pencil beams and ensure that ghost foci are formed away from optical components.

The 1 ns baseline performance model requires 750 J at 1053 nm at the output of the TSF. This implies 3.5 J in the reverser section and 10 mJ injected into the TSF. The extraction efficiency from the amplifiers, in this 1 ns case, is 17%.

C. Long Pulse Beam Transport

Following amplification, the beam is directed into the target hall, where it is immediately frequency converted to the third harmonic. Two 322 mm aperture, solgel-coated KDP crystals are used to achieve this, housed within a single module. The first is 14 mm thick and cut for type I frequency doubling. The second, 12 mm thick, is cut for type II mixing of the unconverted light with the second harmonic, yielding 351 nm output. The input beam is polarized horizontally, as is the 351 nm output (the intermediate second harmonic is vertically polarized). At the nominal operating point, the incident intensity is roughly 1 GWcm\(^{-2}\).

Following frequency tripling, a series of five dichroic mirrors transport the pulse to the target chamber. The beam transport accomplishes the following: it rejects the residual 1053 and 527 nm light, it converts each stack of five beam lines into a conical geometry at the target chamber, and it rotates the beams such that the polarization on the target is in the radial direction with respect to a five-beam cone (i.e., \(p\)-polarized to a plane orthogonal to both long pulse cones, the “target plane”). The cones of five beams possess mirror-symmetry about the target plane. This means that no beam opposes another through the target chamber. Each beam is at an angle of 50° to the cone axis. The third harmonic beam transport is illustrated in Fig. 4.

The long pulse final optics assembly consists of an insertable corner cube (for monitoring beam pointing into the chamber), a vacuum window, an \(f/4\) aspheric focusing lens, and locations for a continuous phase plate and a target debris shield. Continuous phase plates [7], produced using magnetorheological finishing, have been designed and fielded to produce flat-top focal profiles, which have circular cross section when projected onto the target plane. For example, a continuous phase profile, with peak-to-valley of 44 rad and rms gradients in orthogonal planes of 1.15 rad mm\(^{-1}\) and 0.73 rad mm\(^{-1}\), can yield an eighth power super-Gaussian at the focal plane with major axes 290 μm × 186 μm. This gives a circular super-Gaussian profile when projected onto the target plane.

3. Long Pulse Performance

The performance of the long pulse generation and preamplification system has been described previously [3] and will not be discussed in detail here. Figure 5 shows output energy as a function of seed input for a representative beam-line. Building upon and extending the PROP92 code, developed at Lawrence Livermore National Laboratory [8], we have developed a suite of models to represent the beam line performance, which take into account diffraction, nonlinear refractive index, gain saturation, pulse-shape distortion, and frequency conversion (with or without the phase modulation and dispersion of the SSD system). These are summarized in Table 1.

For example, the fitted curve in Fig. 5 is the output of this model for the beam-line gain saturation. Shown in Fig. 6 is the capability to model the degree of pulse shape distortion at 1053 nm. The dashed trace is derived from a streak camera measurement of a PAM-only shot. This trace has been passed through the beam-line performance model, which calculates the new pulse shape, shown in gray, assuming amplification to the measured value of 725 J. The black trace is the measured output pulse on a real 725 J shot and shows good agreement with the model prediction. (The model has yet to be verified for the

![Fig. 4. Schematic representation of the third harmonic beam transport. Beam paths are symmetric about the target plane.](Image)
351 nm pulse shape, because of difficulties in transporting the pulses to the UV streak camera.)

The wavefront of the long pulse beams must be manipulated in order to maintain the required focal spot size of less than 100 μm at the 90% energy contour. This is accomplished by a statically deformed mirror, positioned at the end of reverser section. A saddle shape is imposed on this mirror by mechanically stressing the substrate. The predominant aberration to be corrected is the prompt, pump-induced cylindrical astigmatism that is seen during the flashlamp discharge. To a lesser extent, a thermal aberration of roughly 1.5 waves of astigmatism builds up during a working day. We aim to correct both the prompt and the longer lived-thermal aberration for the “middle shot of a typical day” (i.e., the third) with the introduction of approximately 5 waves (peak-valley) of astigmatism. Figure 7 shows the far-field profile of a typical shot at 1053 nm and the corresponding measured wavefront, using the statically deformed mirror. During operations, the inter-shot period is dictated by the requirement to insert and realign the next target. A repetition period of 60–90 min is typical. The long pulse beams have been fired with a repetition period of ~45 min for up to six shots, at which point a longer cool-down period is required to avoid clipping on the TSF pinholes. When the system is used with phase plates, the beam line aberrations have a negligible impact on the focal plane irradiance.

Figure 8 shows the near- and far-field profiles of the beam after frequency conversion to the third harmonic. Although the wavefront is not measured at 351 nm, the similarity between the 1053 and 351 nm far-field profiles engenders confidence that any aberrations in the diagnostics stations are negligible. Pinhole camera measurements of x-ray spots generated on a foil target, with optimally focused long pulse beams, indicate x-ray spot sizes of around 70 μm, which are consistent with the optical data in Fig. 8. In addition to these beam profiles, energy, pulse contrast, and temporal profiles are measured in each beam line at 351 nm.

### Table 1. Long Pulse Beam-line Model Description

<table>
<thead>
<tr>
<th>Code Name</th>
<th>Physics Described</th>
</tr>
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<tbody>
<tr>
<td>PROP 92 [8]</td>
<td>Spatial and temporal resolution</td>
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<tr>
<td></td>
<td>Diffraction</td>
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<tr>
<td></td>
<td>Wavefront aberration</td>
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<tr>
<td></td>
<td>Nonlinear refractive index</td>
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<tr>
<td></td>
<td>Gain saturation</td>
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<td></td>
<td>Pulse shape distortion</td>
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<tr>
<td>Third harmonic generation [9]</td>
<td>Spatial and temporal resolution</td>
</tr>
<tr>
<td></td>
<td>Type I and type II phase mismatch</td>
</tr>
<tr>
<td></td>
<td>Angular dependence of nonlinear coefficients</td>
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<tr>
<td></td>
<td>Double refraction (walk-off)</td>
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<td></td>
<td>Group velocity delay</td>
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<tr>
<td></td>
<td>Temporal and spatial phase modulation (for SSD)</td>
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<td></td>
<td>Self-phase modulation</td>
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<tr>
<td></td>
<td>Absorption</td>
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<tr>
<td></td>
<td>Diffraction</td>
</tr>
<tr>
<td>Long pulse (LP) beam pulse shape</td>
<td>Temporal resolution</td>
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<td></td>
<td>Reverse THG via look-up table</td>
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<tr>
<td></td>
<td>Reverse gain saturation</td>
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<td></td>
<td>Reverse pulse shape distortion</td>
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<tr>
<td></td>
<td>AWG set point calculation for IO modulators</td>
</tr>
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</table>

Fig. 5. Measured fundamental 1053 nm output energy and modeled beam-line performance.

Fig. 6. Streak camera measurements at 1053 nm of the input (dashed) and output (black) temporal profiles of a long pulse beam-line. Modeled output pulse shape, based on the measured input pulse shape and the measured energy, is shown in solid gray.

Fig. 7. (a) Representative far-field image at 1053 nm. (b) Associated measured wavefront of a long pulse beam-line. Peak-valley wavefront error is 2.8 waves.
The conversion efficiency was optimized over many shots, adjusting the crystal assembly in one axis to tune doubling efficiency and the other to optimize mixing. Figure 9 shows the measured conversion efficiency over a range of angles about each axis with a 0.5 ns square pulse and a nominal 200 J input energy. Also shown are the results of our frequency conversion model. The deviations from a smooth curve are a result of input energy fluctuations, which were included in the model. The data suggest that the model overestimates the width of the tuning curves slightly, but that it works well at the angle of use.

To date, all of the long pulse beam lines have been fired onto target with greater than 400 J in a 1 ns square pulse, with no deleterious effects seen. Frequency conversion efficiency has been measured as 70% for such pulses.

4. Short Pulse Laser Description

A. Pulse Generation and Preamplification

The short pulse generation, stretching, and optical parametric preamplification constitute the optical pulse generation 2 (OPG2) subsystem, which is housed in a room below the laser hall and is described in [10]. It also includes a compressor to facilitate diagnosis of the subsystem performance. The two short pulse beam lines share a common oscillator, so as to achieve the best interbeam jitter performance. This is a Newport Spectra-Physics Tsunami system, tuned to a central wavelength of 1054 nm. The system is locked to an external 80 MHz clock signal, which forms the basis of the Orion timing system. A jitter performance of 10 ps rms is achieved between the short and long pulses. A bandwidth of 12 nm (FWHM) is realized by the oscillator. A Pockels cell selects the single pulse to be injected into both the laser chains and this pulse is split before progressing to each beam-line’s stretcher system. Independent stretchers facilitate ease of compression optimization and the ability to detune each beam-line by an amount defined by the user. Pulse lengths of up to 20 ps are called for in the facility specification. The stretchers are an Offner triplet design, with an effective grating separation of 3.25 m. Each consists of two stretchers, one on top of the other, which are double-passed. The result-ant chirp rate is \(300 \text{ ps nm}^{-1}\) and the hard-clip bandwidth is 18 nm. Hence, all the energy is contained within 6 ns duration.

The output from each stretcher, of roughly 1 nJ energy, is propagated to the input of each beam line’s optical parametric chirped pulse amplifier (OPCPA). Both OPCPA systems are pumped by a single Nd:YAG system (a custom system produced by Continuum Inc.), which produces 532 nm temporally square pulses, of 6 ns duration, with a flat-top spatial profile. The gain is achieved in three stages, with pump beam diameters of 3, 3, and 6 mm and a pump intensity of \(\sim 400 \text{ MW cm}^{-2}\) in each stage. Care is taken to ensure that the injected pulse from the stretcher overfills the pump beam both spatially and temporally to minimize amplified parametric noise. Also, the beam from a preceding gain stage is carefully overlapped with the subsequent pump beam. A noncollinear angle of 0.5° between pump and signal beams is used and the idler removed in the far-field at intervening spatial filters between gain stages (due to its high energy after stage 3, it is here removed in the near-field). All pump beams are carefully image-relayed to the OPCPA crystals to maintain the high beam quality of the pump laser. The amplified pulse is also image-relayed between stages. Each gain stage uses two lithium triborate crystals, using a walk-off compensated orientation and type I phase matching. The 6 ns long pump pulse dictates modest pump intensity. Therefore, relatively long interaction lengths are necessary. The crystal lengths in stage 1 are 20 and 20 mm; in stage 2 they are 30 and 30 mm; and in stage 3, 10, and 20 mm.
These crystal lengths were found to be the best compromise between ensuring signal pulse saturation and controlling the growth of amplified noise. The signal pulse is saturated in both stages 2 and 3 (i.e., amplified to the point of back-conversion). In this regime, the signal tends to adopt the spatiotemporal properties of the pump beam, namely flat spatially and temporally, with 6 ns duration. Allowing this to happen twice ensures that a high quality signal beam emerges from the OPCPA system, with a roughly square spectrum. The output from each OPCPA system is ~150 mJ, during operations, although more has been produced during commissioning. The OPCPA design was informed by a simple, time-resolved model of the OPA equations, with no spatial resolution. The nonlinear coupling coefficient and the phase mismatch were modified to provide a match with the published performance of another OPA system with a high quality, flat spatiotemporal pump profile, albeit with differing operating parameters [11]. The ultimate performance of our system matched this model’s predictions well and only modest empirical optimization was required.

The pulses from the OPCPA stages are directed through apertures in the ceiling into the laser hall, where they are image- relayed into a four-passed short pulse rod amplifier (SPRA) stage. This uses a design similar to the rod amplifier stage on the long pulse PAM, except that two amplifier heads, housing different laser glasses, are used. A phosphate (LHG-8) and a silicate (ED-2) glass are used, which act together to mitigate the bandwidth loss, such that 9 nm FWHM emerges from the rod amplifier, with a nominal output energy of 2 J in a 16 mm diameter beam. The SPRA contains an in-house designed beam apodizer to compensate the gain profile across the aperture of the rods. Whereas in the PAM the Gaussian shape of the regenerative amplifier beam can compensate this effect, the OPCPA output is flat and so the beam edges must be artificially attenuated relative to its center. The apodizer uses pixels of metallic coating, generated by a Floyd Steinberg error-diffusion algorithm, deposited on a glass substrate and then spatially filtered. This algorithm tends to throw power further out in the far-field than, say, a random noise algorithm, facilitating effective spatial filtering [12].

B. Short Pulse Amplifier Chain Design

A schematic of the short pulse amplifier chain is shown in Fig. 10. On emerging from the SPRAs, the beam is expanded to 86 mm and directed into a Faraday rotator after a thin-film polarizer. This rotator enables a double pass of a 100 mm aperture disk amplifier, which consists of six LG770 glass slabs, excited by 8 flashlamps and a bank energy of 100 kJ. All the disk amplifiers in the facility are of similar design, scaled appropriately. The pulse energy after this amplifier is roughly 50 J on a full power shot.

The retroreflecting mirror adjacent to the 100 mm aperture amplifier is the beam-line’s deformable mirror. This is a 63 element monomorph mirror, manufactured by Cilas. The associated wavefront sensor (HASO3, from Imagine Optic) that completes the adaptive optics (AO) system is positioned in a diagnostics station at the output of the amplifier chain, prior to the compressor.

After the second pass of the Faraday rotator, the beam’s polarization is rotated by 45° using a wave plate. The beam is expanded to 140 mm diameter and injected into a 150 mm aperture disk amplifier with four slabs of LG770 glass, driven by a bank energy of 100 kJ. The laser energy is increased to about 150 J. There follows a 150 mm aperture Faraday isolator to mitigate back-reflections from the target before the beam is expanded to 180 mm diameter. Three 200 mm aperture amplifiers, identical to those used on the long pulse beam lines, bring the nominal output energy to about 700 J. Given the system losses through the remaining beam transport and the compressor system, this is the energy required to deliver the specified 500 J to target. Finally, the beam is expanded to 600 mm diameter for injection into the pulse compressor system.

The total stored energy in all the beam line disk amplifiers is calculated to be 5.22 kJ and so the extraction efficiency is 13.4%. The extracted energy is limited by a design criterion that the total spectral phase distortions due to nonlinear refractive index be limited to 1.2 rad. The total beam line energy is ultimately limited by the laser damage threshold of the compressor gratings.

C. Pulse Compression System

The compressor comprises two 940 mm diameter, gold-coated diffraction gratings, housed in a large vacuum vessel, along with appropriate transport and diagnostic optics. The gratings have a 1480 mm⁻¹ groove density and are used at 47.9° angle of
incidence and were manufactured by Lawrence Livermore National Laboratory. Their center-to-center separation is 13 m. A single pass of this system is used and so a spatial chirp is manifest in the plane of diffraction of 58 mm nm\(^{-1}\) on the surface of the second grating. Since the bandwidth into the compressor is around 5 nm (FHWM), some energy falls off the second grating. (By comparison, a monochromatic beam projects a major-axis of 895 mm on the face of the second grating.) Nevertheless, system modeling demonstrated this to be the optimal configuration in terms of intensity on target.

The compressed pulse is diagnosed using leakage through the first postcompressor turning mirror. The full beam is down-collimated to 40 mm with a Galilean telescope within the vacuum vessel, before image relay onto a separate diagnostic optical table. A remotely driven 99% reflecting mirror can be inserted within this telescope to limit the phase due to nonlinear index (“B-integral”) in the diagnostic optics to less than 1 rad. This can be replaced by a blank optic to facilitate alignment with low power beams with no net change in focus.

D. Short Pulse Beam Transport

Postcompression, the short pulses are transported to the target chamber under vacuum. Turning mirror chambers, housing 940 mm diameter 45° mirrors, facilitate the required beam path from the compressor hall to the target hall and into the interaction chamber. Each beam is focused to target using an \(f/3\) parabola. One beam is focused parallel to the axis of the five-beam cones of the long pulse system; the other is focused orthogonal to this, both in the horizontal plane. The focusing optics are held in hexapod mounts. These compact mounts can rotate the optic about an arbitrary point in space. By moving the mirrors about a point \(2f\) from the optic, the angle of incidence onto the parabola can be adjusted without inducing a lateral movement of the focal spot. Thus, aberrations in the system can be minimized while continuously viewing a low power alignment beam on a microscope near the focus.

E. Frequency Doubling One Short Pulse Beam

Within the vacuum transport of one of the short pulse beams an additional chamber holds the necessary equipment to frequency double the compressed pulse, which can be fielded optionally, depending on the experimental requirements. This capability was designed into the facility to provide high pulse contrast operation if required. At the inception of the project, pulse cleaning techniques, such as double CPA [13] or short-pump-pulse OPCPA [14,15] were not well developed. Moreover, operation of a short pulse beam at 527 nm can enable a different regime of laser-plasma interactions to be studied. Modeling indicates that a thickness of 3 mm of KDP, using type I doubling, gives the best performance over the range of pulse durations envisaged to be most likely used in experiments (i.e., 0.5–5 ps). Unfortunately, it is not possible to manufacture a 3 mm crystal at our full aperture of 600 mm. Therefore, the maximum available size of 325 mm clear aperture was used.

Upon entering the doubling chamber the beam is apodized to 300 mm, using absorbing glass, before being reflected onto the KDP crystal. This mirror is dichroic, allowing a 527 nm CW alignment beam to be injected into the system at this point. Three further dichroic mirrors within the chamber return the beam to its original path and remove unconverted fundamental light. A different parabola is used when operating in this mode, which also improves the spectral discrimination. A diagnostic pick-off is taken through the second dichroic after the doubler, when the power at the fundamental has been reduced to manageable levels.

The parabola for the 527 nm beam has the same 1800 mm focal length as the fundamental beam, corresponding to \(f/6\) focusing. This means that the focal spot size is the same as the \(f/3\), 1054 nm beam. Optimization of the parabola aberration is accomplished by adjusting the optic’s angle of incidence. Output from the OPCPA, without further amplification, is used, viewed on a target-plane-viewing microscope. The doubling efficiency of this source is adequate for this purpose. More detail of the doubling scheme design and its performance is given in [16].

5. Short Pulse Performance

The short pulse generation and preamplification system have been reported elsewhere [10] and will not be discussed in detail in this paper. Figure 11 shows the output near-field and spectrum of one of the OPCPA systems, exhibiting the expected top-hat spatial profile and flat spectrum. In the design phase of the project, it was decided to inject only the central 32% of this beam diameter into the laser chain, as mitigation against potential irregularities in the OPCPA output near-field profile. As can be seen, this was unnecessarily pessimistic.

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Fig. 11. Input/output spectra of the OPCPA preamplifier and (inset) the output near field profile.
In the rod amplifier stages, the gain contributions from the phosphate and silicate rods were adjusted to optimize the output spectrum. Figure 12 shows the all-phosphate, all-silicate, and net output spectra from the optimized rod amplifier, prior to disk amplifier injection.

The energetics performance of the short pulse beam lines is illustrated in Fig. 13. Output energy is plotted against the operator set-point of the OPCPA system. The fitted curve is a simple gain saturation model that is used by the operator to define the system configuration to achieve a given output energy. This initial data indicates that the system can deliver the requested energy to within about 5%, for high energy shots.

Figure 14(a) shows the near-field output immediately after the final amplifier. Since the compressor design uses a single pass of two diffraction gratings there is some lateral dispersion of the beam post-compressor. As can be seen in Fig. 14(b), some of the beam is lost from the edges of the second grating (this image includes additional minor clips on the beam transport to the compressed pulse diagnostics station, plus artifacts from the grating writing process in the center). The spectrum at the output of the disk amplifiers is shown in Fig. 15. Since a vacuum-compatible calorimeter was not available, the fraction transmitted to target must be calculated. Modeling indicates that 10% of the beam energy falls outside the second grating surface. In addition to the measured 91% diffraction efficiency of each grating, this yields 75% transmission through the compressor system. Transport mirror coatings are sufficiently broadband not to modify the pulse spectrum significantly.

Figure 16 shows a sample second-order, single shot autocorrelation taken using an in-house built device. This measurement is taken using almost the entire beam aperture. The width is 1.15 ps, suggesting a pulse width of around 0.75 ps. In practice, this diagnostic exhibited substantial variation in measured pulse width and shape, from shot to shot, with identical shot parameters. It is the subject of future work to identify to what extent this fluctuation is real or an artifact of the diagnostic.

To illuminate this uncertainty, two additional temporal diagnostics were fielded in parallel on the same shots. Unfortunately, this precluded the simultaneous use of the in-house autocorrelator. One was a Wizzler [17], a device that performs spectral interferometry on the pulse using a self-generated cross-polarized wave signal as the reference pulse. The other, a Grenouille [18], is a single-shot frequency resolved optical gating system, similar to the in-house autocorrelator, but with a thicker doubling crystal, which is used to extract spectral information. Each system samples about half the beam aperture. The results from each diagnostic are shown in Fig. 17 on a shot which yielded 500 J on target. Each device
calculates a suggested temporal profile, which has been scaled to give a plot of instantaneous power. The pulse durations broadly agree, at around 400–500 fs, although the detailed structure outside the main pulse differs. Taken at face value, these traces show a peak power of ∼1 PW. Further work, in particular to diagnose any variations in delay over the large beam aperture, is planned.

Achieving the best possible focal spot on target requires correction of the following wavefront contributions: prompt pump-induced distortion, longer-lived thermal effects, and static optical aberrations. The latter two terms can be corrected in a straightforward manner using the AO systems. To correct the prompt aberration, this component was characterized over several shots and the opposite aberration added to the target wavefront of the AO system. A further source of aberration was considered, namely that of the compressor gratings. To achieve best compression, a flat wavefront is required between the two gratings. Our strategy was to characterize the wavefront of the first grating and use the AO system to correct for this. Further aberration caused by the second grating is mitigated by tuning the angle of incidence onto the focusing parabola. The wavefront sensor of the AO system is positioned prior to the compressor and so cannot interrogate the gratings.

When operating in frequency doubled mode, the relevant short pulse beam exhibits broadly flat doubling efficiency with respect to input energy (∼60%) around the region of use. Because of the dispersion onto the second compressor grating, the fluence is slightly enhanced near the central region of the beam. Therefore, the energy transmitted through the apodizer onto the doubling crystal is greater than would be the case with a spatially flat beam, enabling the incident energy to exceed 170 J. The resultant second harmonic energy is 100 J. The principal objective of doubling the pulse is to improve temporal contrast. Prior to doubling, the pulse is preceded by a 3 ns pedestal, at ∼10−8 of the peak power, attributed to amplified noise in the OPCPA system. Upon doubling, this is reduced to ∼10−14. To date, diagnosis of the second harmonic pulse has been limited to energy on target and nanosecond contrast. This system is described in greater detail elsewhere [16].

6. Summary

The designs of the laser systems of the Orion facility have been presented, as has the performance achieved to date. Each of the long pulse beams has been fired at above 400 J with a 1 ns pulse. Their focusability and stability in terms of pointing, timing,
and power have been demonstrated. Both short pulse beams have delivered ~500 J to target at the fundamental wavelength. One beam-line has yielded greater than 100 J at the second harmonic in a subpicosecond, high contrast pulse. The facility is now deemed ready for the commencement of the experimental program.

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References